Low-Temperature Characteristics of Semiconductor Injection Lasers

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Abstract—**Many optoelectronic devices have improved characteristics when operating at reduced temperatures. In this paper, we review the low temperature effects on the wavelength, gain, threshold current, phase and intensity noise, reliability, and carrier freezeout in semiconductor injection lasers (with emphasis on AlGaAs devices), and their influence on the lasers' applications.**

I. Introduction

The first generation of GaAs semiconductor injection lasers [1] operated at cryogenic temperatures. Poor carrier confinement and weak optical guiding—both byproducts of the homostructure construction of the devices—resulted in very high room-temperature threshold-current densities ($\sim$50–100 kA/cm^2), which precluded their CW operation at 300 K. During the seven years following the first demonstration of lasing action in semiconductors, intensive research efforts were expended towards realizing Kroemer's idea of incorporating heterojunctions in the laser structure, thus providing sufficient waveguiding and carrier confinement to enable room-temperature CW operation. CW operation at 300 K was first demonstrated in 1970, and this helped transform semiconductor lasers from laboratory curiosities into mass-produced solid-state devices. Today, most semiconductor lasers that are used in optical communications, optical recording, and similar applications are not cooled to cryogenic temperatures (which is one of their attractive features). These include devices fabricated of the AlGaAs and InGaAsP systems, that emit light in the 0.75–0.9 μm and 1–1.6 μm wavelength ranges, respectively.

The purpose of this paper is to discuss the implications of low-temperature operation of semiconductor lasers. In Section II of this paper we review the temperature dependence of some of the physical characteristics of semiconductor lasers and point out the possible advantages in low-temperature operation, which may be significant in some specialized applications. (By "low temperatures" we refer to the temperature range below room temperature to cryogenic temperatures.) In Section III some of the practical aspects of low-temperature operation of semiconductor lasers are discussed. It is shown that the semiconductor laser has to be properly designed in order to realize the benefits associated with low-temperature operation in practical applications.

In addition to the AlGaAs and the InGaAsP lasers which operate in the near infrared, there are several types of semiconductor lasers that operate in the mid-to-far infrared region ($\sim$3–30 μm) of the electromagnetic spectrum [2]. These lasers are based on various IV–VI atomic systems of lead salts (e.g., PbSnSe), and they require operation at low temperatures (usually below $\sim$120 K), probably because of increased free carrier absorption (which is approximately proportional to the square of the wavelength) and increased rate of Auger recombination (which is higher in low bandgap materials). At low temperatures the concentration of free carriers, and hence the magnitude of these two effects, is smaller, thus making it possible to establish sufficient gain for lasing without excessive levels of current densities [3]. Employing a quantum-well structure, operation at higher temperatures (174 K CW; 241 K pulsed) has been recently demonstrated [4]. These lasers will not be considered further in this paper.

There are also other types of optoelectronic devices that are operated at cryogenic temperatures. For example, several types of detectors, especially those used for photon counting, have to be cooled in order to reduce their dark currents to acceptable levels. This subject will also not be treated in this paper since it can be found in several texts [5].

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II. Low-Temperature Effects in Semiconductor Lasers

In this section we describe the temperature dependence of some of the physical parameters of semiconductor lasers. Unless otherwise noted, all the results are obtained using parameters of lasers fabricated of the AlGaAs ternary system, although they also qualitatively pertain to quarternary (i.e., InGaAsP) lasers.

A. Emission Wavelength

The photon energy of the radiation emitted by the laser approximately equals the material bandgap energy (more detailed information is given in the next subsection). Since the bandgap energy increases at reduced temperatures for most semiconductors (e.g., in GaAs $Eg(T) = 1.519 - 5.405 \times 10^{-4}T^2/(T + 204)$ eV [6]), such lasers will lase at shorter wavelengths when cooled. For example, in GaAs the peak of the spectral gain curve shifts from $\sim$0.9 μm to $\sim$0.84 μm as the temperature is reduced from 300 K to 77 K. (It is interesting to note that in the lead salt lasers $dEg/dT > 0$, and thus the lasing wavelength increases upon cooling.)

Recently there has been considerable interest in extending the operation of AlGaAs into the visible region of the spectrum. Operation at shorter wavelengths is desired in applications involving optical recording and free-space optical

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communications because of the smaller diffraction angles. This is usually accomplished by increasing the aluminum fraction in the active region material [7] and by fabricating it from a single or multiple quantum wells [8]. Using these techniques, operation well below 700 nm has been achieved without paying an excessive penalty in increased threshold current density. By cooling the laser we can achieve even a further (and considerable) reduction of the lasing wavelengths.

B. Gain and Threshold Current

The optical gain in the semiconductor laser material depends on the density of states in the conduction and valence bands and the Fermi-Dirac statistics of the electrons and holes occupying them [9]. At higher temperatures, the carrier energy distribution is wider. This implies that (a) higher current density must be pumped into the active region in order to achieve the same gain, and (b) the width of the spectral gain curve increases.

An example of calculated gain curves for GaAs at 297 K and 77 K is shown in Fig. 1 [10]. We see that at 77 K, the same gain values can be achieved at much lower current levels. For gain levels, g, relevant to laser operation ($\sim$30-150 cm^{-1}), the dependence on the carrier concentration, N, in the active region is often expressed by the following empirical formula

$$g=\frac{A}{v_g}(N-N_{om}) \tag{1}$$

where A is the differential gain coefficient, N_{om} is the carrier density needed for transparency, and v_g is the group velocity of the laser mode. For GaAs at 300 K, $A \simeq 2\cdot10^{-6}\ cm^3\cdot sec^{-1}$ and $N_{om} \simeq 7.5\cdot10^{17}\ cm^{-3}$. At 77 K there is a large improvement in these parameters: A is increased to $\sim 10^{-5}$ $cm^{-3}\cdot sec^{-1}$, and N_{om} is reduced to $\sim 10^{17}\ cm^{-3}$ [11]. A reasonable fit to the calculated data is that A varies approximately as $1/T$, and that N_{om} is approximately proportional to $T^{1.5}$ [9]. From Fig. 1 we can also see that the spectral width of the gain spectrum at 77 K is approximately one half of the room-temperature value.

The lasing threshold occurs when the modal gain of the lasing mode equals the total modal loss. Since the losses (mirror losses and distributed losses) are very weak functions of temperature, higher gain at lower temperatures implies lower threshold-current densities, lower heat dissipation in the device, and higher overall efficiency. In many cases the temperature dependence of the threshold current density of semiconductor lasers over a certain temperature range is expressed by the following empirical formula [12]

$$J_{th}(T_2)=J_{th}(T_1)e^{(T_2-T_1)/T_o} \tag{2}$$

where T_o is a characteristic device parameter (often two or more values of T_o are defined over different temperature regions: in quartenary lasers, for example, T_o is higher at lower temperatures [13]).

Although these improvements may not be so important in today's low-threshold lasers, they may be more significant in laser arrays [14], and in applications such as free-space communications where passive radiative cooling is feasible.

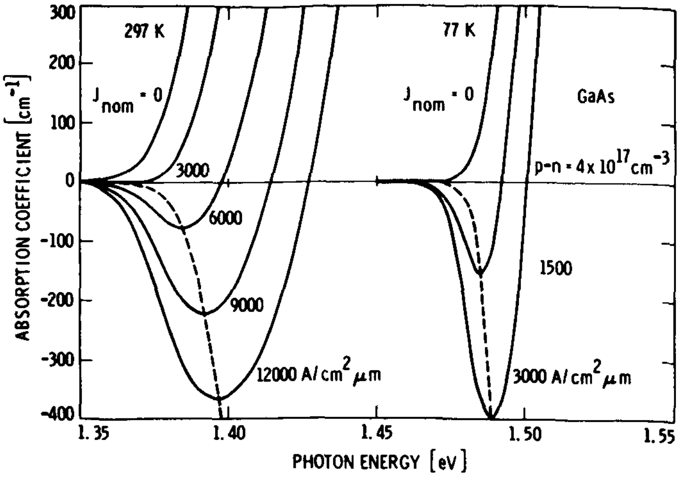

Fig. 1. Calculated absorption coefficient $\alpha = -g$ of GaAs at 297 K and 77 K versus photon energy for several values of nominal current density (i.e., current density divided by the active region thickness). The dashed line gives the photon energy of the gain peak as a function of the maximum gain [10].

C. Speed of Response

Perhaps the biggest incentive for low-temperature operation is the possibility of modulating the laser at higher rates. The characteristic parameter for the speed of response is the resonance frequency, f_{res}, which sets the upper limit of useful small-signal modulation. While the large-signal response is more complicated to calculate, higher f_{res} also means faster large-signal response. The resonance frequency is given by [15]

$$f_{res} \simeq \frac{1}{2\pi}\sqrt{\frac{AS_o}{\tau_{ph}}} \tag{3}$$

where A is the differential gain coefficient discussed previously, S_o is the (DC) photon density in the laser cavity, and τ_{ph} is the photon lifetime. Increasing f_{res} by increasing S_o is limited by reliability considerations; reducing τ_{ph} carries the penalty of higher threshold currents. However, when the laser is cooled, A increases, as shown in the previous subsection. The problem of the ultimate limits of the frequency response has been analyzed in [16], and small-signal modulation bandwidths exceeding 10 GHz have been demonstrated by cooled operation [17]. Because the lasers in that experiment were measured only down to $-70°C$, the improvement in f_{res}, shown in Fig. 2 is not as large as could have been obtained at cryogenic temperatures. However, it is somewhat larger than what is predicted by the theoretical gain calculations discussed in the previous subsection. This may indicate the possibility of even larger material gains—and hence further performance improvement—at lower temperatures. Recently developed quartenary lasers have demonstrated small-signal 3 dB bandwidths of 16 GHz and 26.5 GHz at 20°C and $-60°C$, respectively (the 3 dB bandwidth is approximately 50 percent larger than f_{res}).

D. Linewidth and Noise

In applications that rely on the coherent aspects of the semiconductor laser radiation (e.g., heterodyne detection), it is desirable to have lasers with linewidths as narrow as

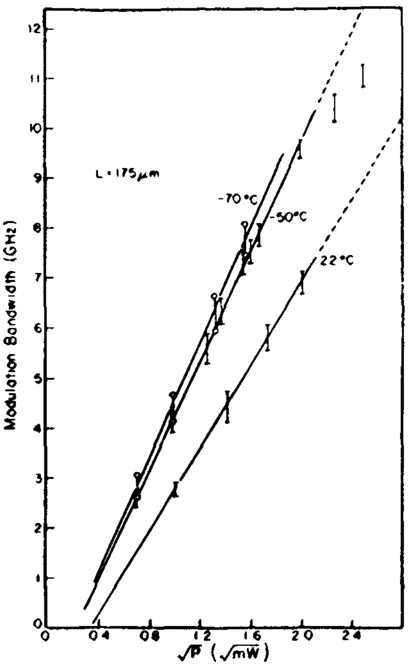

Fig. 2. Variation of modulation bandwidth (f_{res}) with the square root of the emitted optical power $\sqrt{P}$ [17].

possible. The linewidth, $\Delta\nu$, of the semiconductor injection laser, which is a manifestation of its phase noise, has two components. The first component, denoted by $\Delta\nu_p$, is due to coupling of spontaneous emission into the laser mode, resulting in the inverse power dependence of the modified Schawlow-Townes formula [18]

$$\Delta\nu_p = \frac{h\nu E_{cv} v_g \ln \frac{1}{R}}{8\pi L}(1+\alpha^2)\frac{1}{P} \tag{4}$$

where ν is the laser frequency, E_{cv} is the spontaneous emission rate into the lasing mode, L is the laser length, R is its mirror reflectivity, α is the linewidth enhancement factor, and P is the output power of the laser. The second component, denoted by $\Delta\nu_\infty$, represents a power-independent linewidth broadening that can be explained in terms of fluctuations in either the electronic state occupancy associated with fast intraband thermalization [19] or the number of carriers in the active region [20]. Experimental results of linewidth measurements in a Transverse Junction Stripe (TJS) laser [21] diode are shown in Fig. 3 [22].

The overall effect that cooling has on a laser's linewidth depends on the output power level. At lower power levels the inverse power component, $\Delta\nu_p$, is the dominant contribution to the linewidth. As the laser is cooled, $\Delta\nu_p$ is reduced because of reduction in both the spontaneous emission rate and the linewidth enhancement factor α (which is inversely proportional to the differential gain coefficient A [18]). The ratio of $\Delta\nu_p$ at room temperature to that at 77 K is approximately 8. However, at higher power levels (typically above a few milliwatts), the major contribution to the linewidth is from the power independent component $\Delta\nu_\infty$. As seen in Fig. 4, $\Delta\nu_\infty$ increases at lower temperatures, from 1.9 MHz at room temperature to 8.4 MHz at 77 K. Recently, $\Delta\nu_\infty$ = 30 MHz was measured for a laser at T = 1.7 K [23]. The overall temperature effect on the linewidth thus depends on the output power level of the laser.

In applications where the laser light is not detected coherently, the noise parameter of concern is its intensity noise, often characterized by RIN, the Relative Intensity Noise [24]. Reduction in the RIN is important because it increases the signal to noise ratio of the system where the laser is used. The RIN is defined as:

$$\mathrm{RIN}(f) = \frac{S_f(f)\Delta f}{S_0^2} \tag{5}$$

where $S_f(f)$ is the power spectral density of the photon density, and Δf is the bandwidth. Employing the formulas of [24], RIN(f) at 300 K, 200 K and 80 K is plotted in Fig. 5. As expected, the RIN has a peak at f_{res}. More importantly, the intensity noise levels are reduced at low temperatures; cooling the device from 300 K to 200 K results in a theoretical improvement of approximately 4 dB/Hz. Recent measurements seem to be in reasonable agreement with these calculations; cooling a crank-TJS laser [25] from 300 K to 200 K yielded 5 to 6 dB reduction in the RIN [26]. The accompanying increase in f_{res}, from 8 to 13.5 GHz, was again somewhat larger than that predicted from the theoretical gain calculations.

III. Practical Considerations in Low-Temperature Operation of Semiconductor Lasers

In the previous section we have seen that low temperatures improve many of the material properties relevant to semiconductor laser operation. However, in addition to the basic material parameters, there are other factors that need to be taken into account when considering the actual device operation. In this section we will briefly describe the effects of some of these factors, namely: reliability, carrier freezeout, and ease of operation. In addition, parasitic leakage currents out of and around the laser active region are also reduced at lower temperatures. This may explain why the experimentally observed improvements in some performance characteristics of the cooled devices (e.g., the resonance frequency) is greater than theoretically predicted, as mentioned earlier.

A. Reliability

The issue of reliability of semiconductor lasers is a complex one [27]. There are several degradation mechanisms, and their temperature dependence is not completely known. Most of them, however, are characterized by some activation energy E_a, with the corresponding mean time to failure (i.e., median level lifetime for that particular failure)—assuming the Arrhenius model—being directly proportional to exp (E_a/kT). This means that, in principle, cooling the laser increases its lifetime substantially. With a typical E_a = 0.7 eV, the 77 K lifetime should be many orders of magnitude longer than at 300 K. However, in practice, cooling the device may introduce new degradation mechanisms or reduce the activation energies of existing ones. This can be due to increased thermally induced stresses in the laser active region (caused by thermal expansion coefficient differences between the various

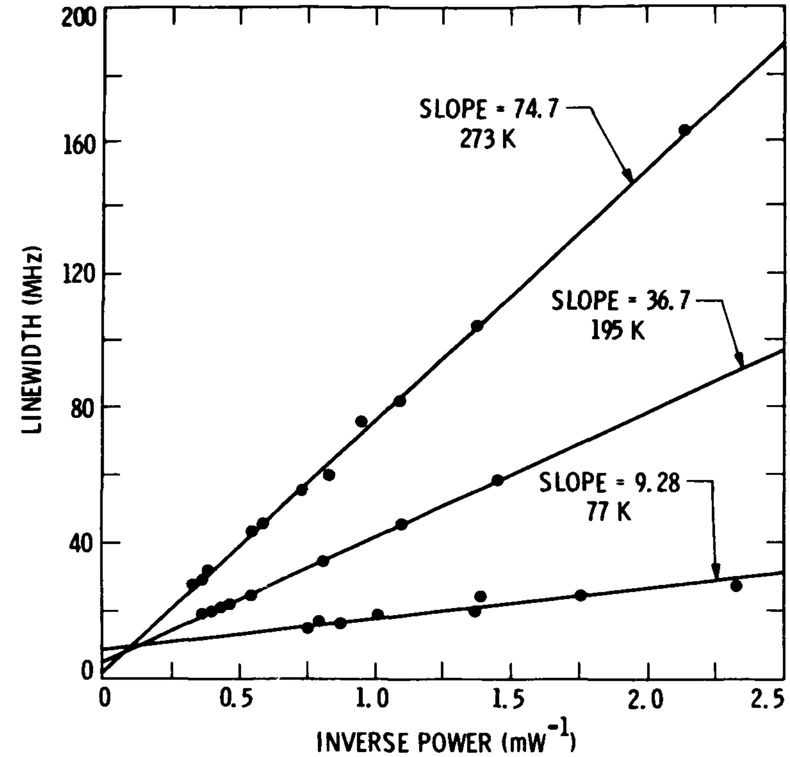

Fig. 3. Laser linewidth as a function of the inverse output power at 273 K, 195 K, and 77 K [22].

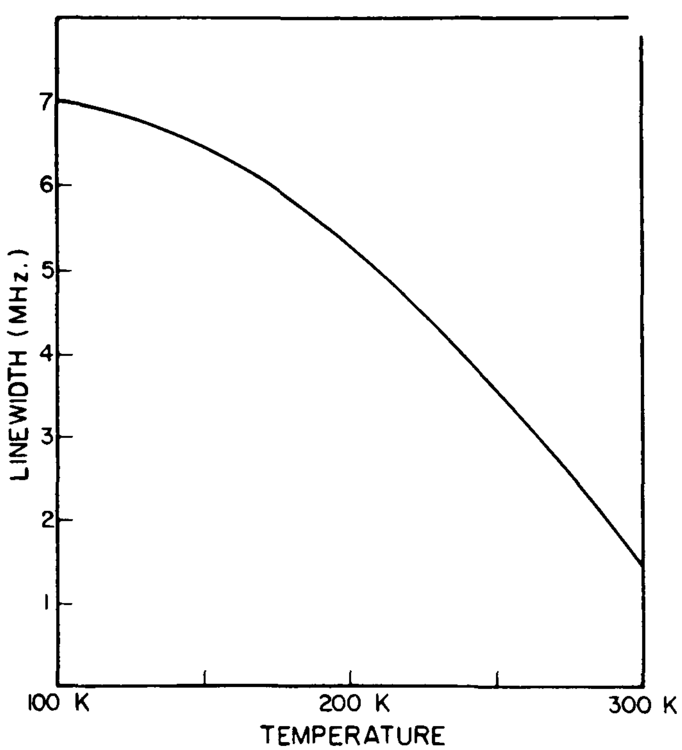

Fig. 4. Calculated power independent linewidth ($\Delta\nu_\infty$) versus temperature [19].

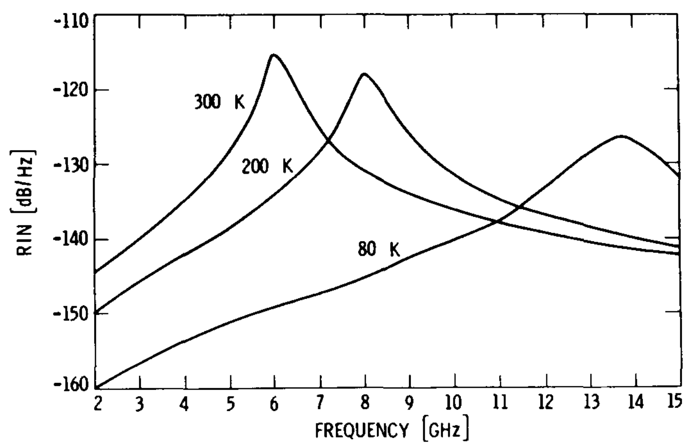

Fig. 5. Calculated relative intensity noise (RIN) of a semiconductor laser at 300 K, 200 K and 80 K.

device regions), degradation of the bonding material, and possibly other factors.

Not much data exist on this problem, since most lifetests are carried out at or above room temperature. Some initial results of lifetests conducted at $-20°C$ [28] seem to indicate that careful device design and proper operating conditions can prevent lower reliability of the cooled devices. First, the cooled lasers have to operate in a clean and controlled environment in order to prevent condensation of water and hydrocarbon compounds on the facet, with the resulting apparent reduction of the light output. Second, the heatsink material and the thickness of the bonding material have to be chosen such that thermal stresses are minimized. With no other modifications in the device structure, the $-20°C$ lifetimes appear to be somewhat longer than at room temperature. It is also interesting to note that no new degradation mechanisms were observed in the cooled devices. Although the above are only initial results, it is clear that special considerations have to be taken into account in the design of a semiconductor laser device when it is intended for cryogenic operation if its reliability is not to be compromised.

B. Carrier Freezeout

As the temperature is reduced below a certain value, fewer carriers are available for current conduction [29]. The temperature below which the freezeout process sets in is higher for dopants with higher ionization energies. The reduction in the carrier concentration causes an increase in the device resistance, as shown in Fig. 6. This leads to lower device efficiency and makes modulation more difficult. The solution to this problem is to increase the doping of the device regions in series with the active region so that they are degenerate or dopant band-tails are formed. This is the situation in the TJS lasers, used for the linewidth measurements discussed previously [20], [22], [23], where all the device layers are heavily doped. Since most semiconductor lasers are constructed differently from the TJS laser, and since it is difficult to establish high doping levels in the p-type cladding layer of common types of semiconductor lasers, this may present a problem in realizing the full benefit of low-temperature operation.

C. Practicality

As mentioned above, one of the major attractive features of semiconductor injection lasers is that—unlike other lasers—they are basically solid-state electronic devices. When semiconductor lasers are put in dewars and cooled to cryogenic temperatures, they become much less attractive in many commercial applications that require the lasers to be available in large quantities and at low prices. (A modest amount of cooling—to $\simeq -50°C$— with thermoelectric coolers is less objectionable since it does not require the use of cryogenic technology.) Thus it seems that semiconductor injection lasers will be used at cryogenic temperatures only in specialized applications where the advantages of low-temperature operation are necessary to achieve certain performance levels. These applications may include, for example, free space communications, very high modulation frequencies, and high-efficiency operation of laser arrays.

IV. Conclusions

Operational characteristics of many optoelectronic devices improve as the devices are cooled to lower temperatures. In this paper we have reviewed the temperature dependence of several parameters of semiconductor injection lasers. It has been shown that the lasers' gain and speed are increased, and the noise levels are generally reduced (with the exception of phase noise at high power levels). However, realizing these improvements may compromise the device reliability if it is not properly designed, and make it less attractive for many commercial applications. Cryogenic operation may be preferred in specialized applications where some required operational parameter values cannot be achieved in uncooled operation.

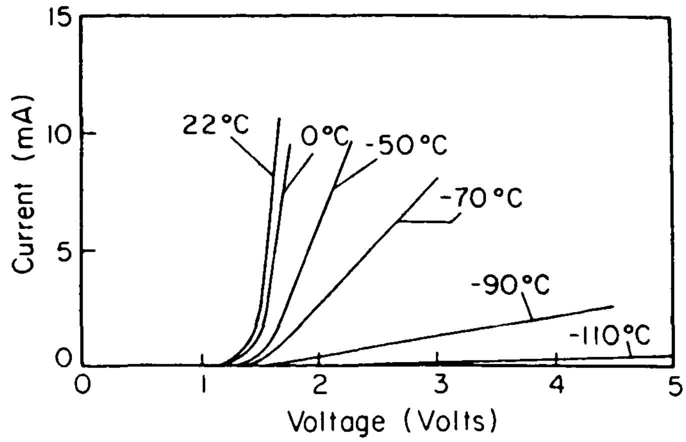

Fig. 6. *I-V* characteristics of a semiconductor injection laser at various temperatures [17].

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